The Athena X-ray Integral Field Unit (X-IFU)

Didier Barret (IRAP, FR)

&

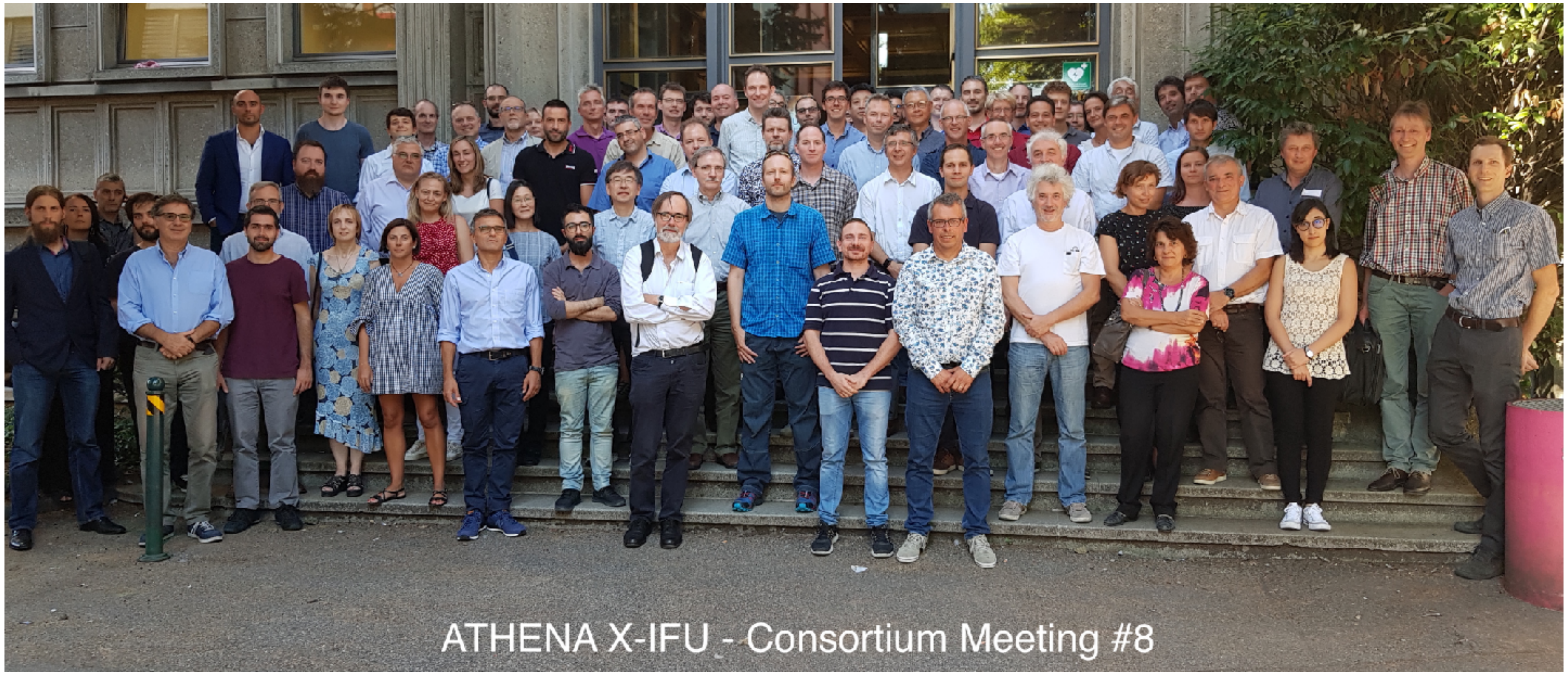
Jan-Willem den Herder (SRON, NL), Luigi Piro (IAPS, IT), Thien Lam Trong (CNES, FR) & Massimo Cappi (INAF-OAS, IT)

on behalf of the X-IFU Consortium

Athena Conference, September 25th, 2018, Palermo

The Athena X-ray Integral Field Unit consortium

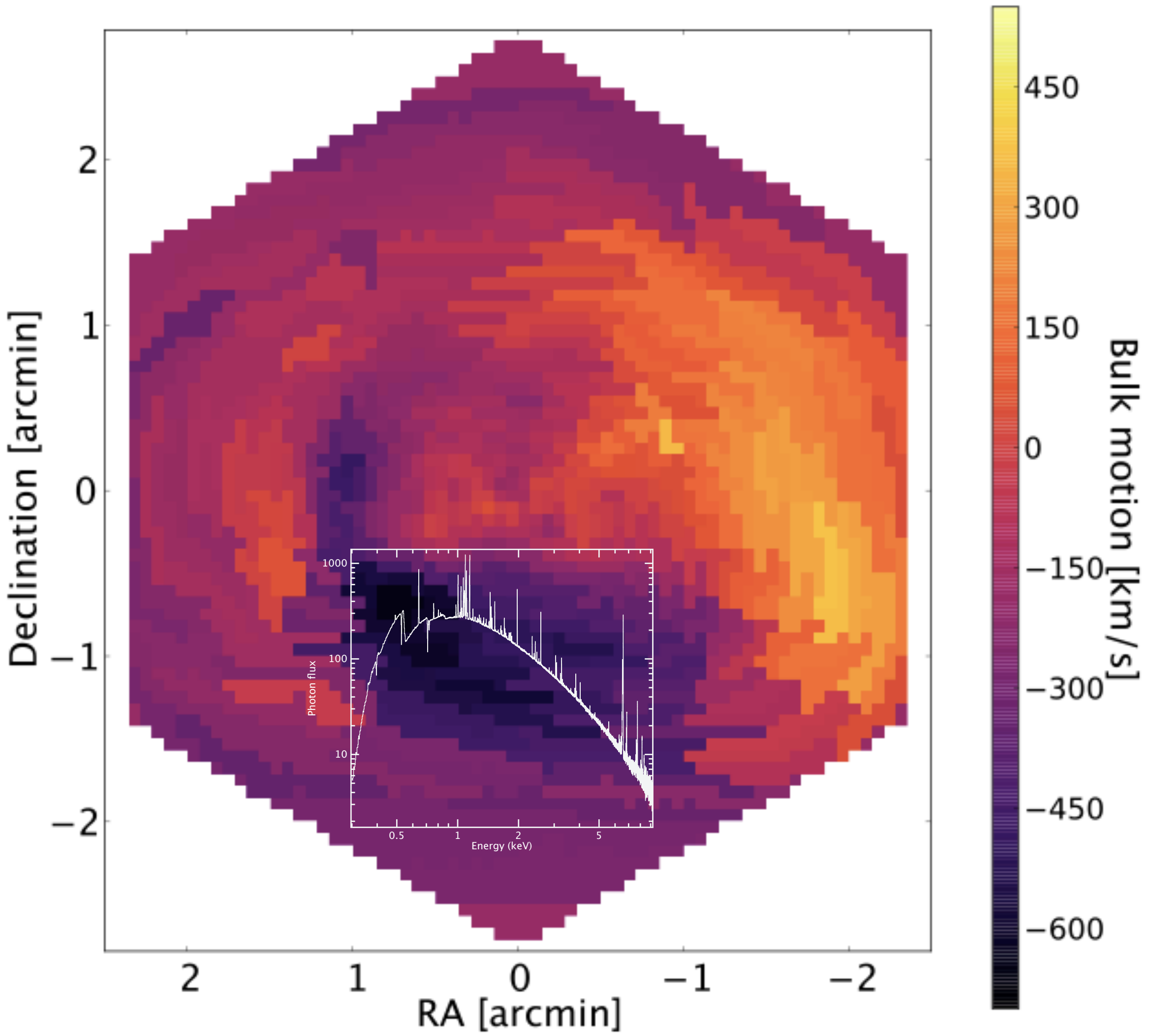
- X-IFU is the X-ray micro-calorimeter of the Athena space observatory
- Built by a Consortium led by France (IRAP & CNES)
  - with Netherlands and Italy as prime contributors
  - and science and hardware contributions from eight other ESA members states (Belgium, *Czech Republic*, Finland, Germany, *Ireland*, Poland, Spain, Switzerland)
  - and key contributions from Japan and the US



X-IFU core science

- Probing the dynamical and chemical state of baryonic matter across cosmic time
  - By mapping hot gas trapped in dark matter potential wells to measure bulk velocities, turbulence, abundances, temperatures, densities…
    - ➡ From the first galaxy groups to the local massive clusters
- Hitomi has unveiled in one single cluster observation the true power of high-resolution spectroscopy, leading to unexpected discoveries

Peille et al. — Cucchetti et al.

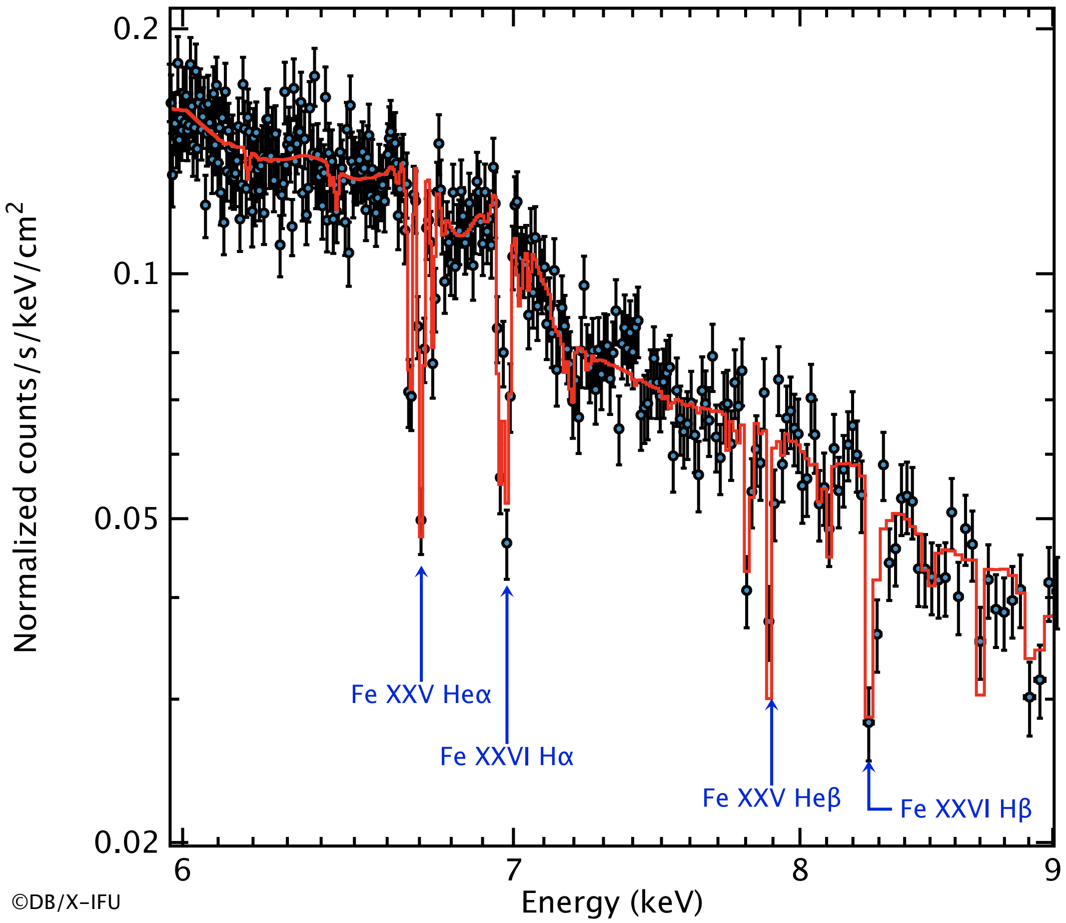


Simulated velocity map of bulk motions of hot plasma in cluster

X-IFU core science

- Probing black holes at work in shaping the Universe and their surroundings
  - By performing time resolved spectroscopy of accretion disks, winds, outflows and jets
  - From the faintest AGN to the brightest X-ray binaries

J. Miller et al.

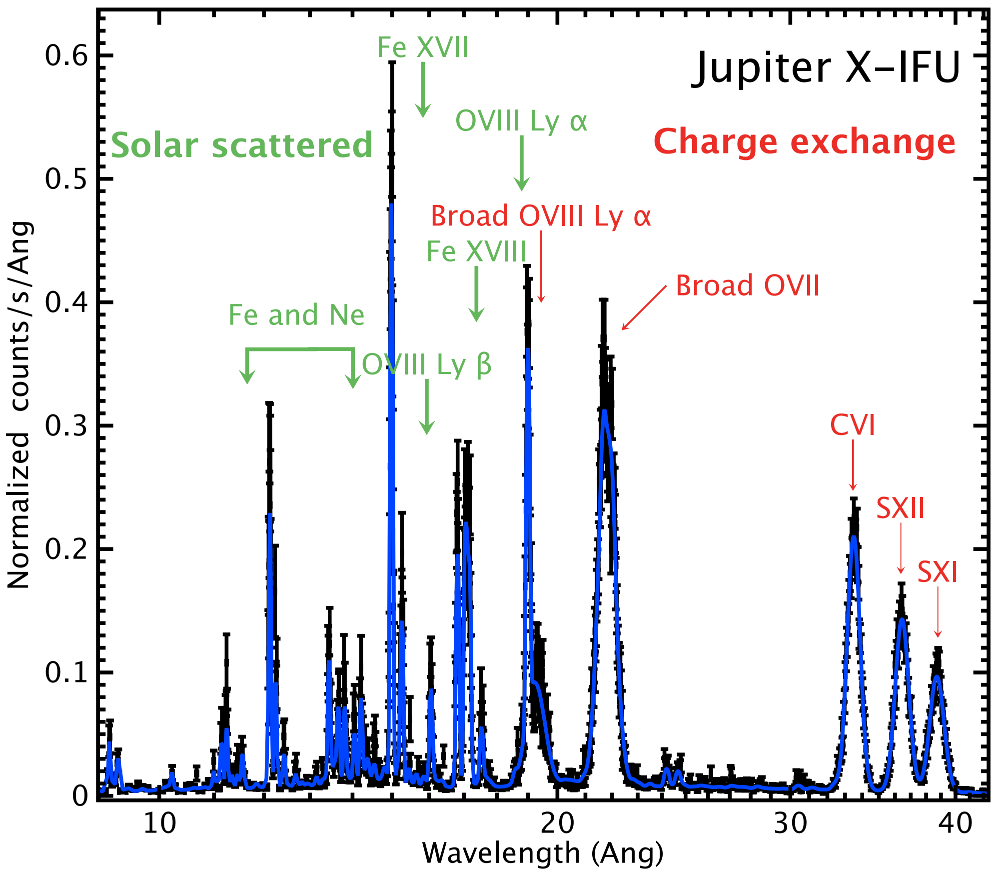


X-ray binary spectrum with high velocity wind absorption features

X-IFU observatory and discovery science

- By providing hot plasma diagnostics in a wide range of astrophysical settings
  - Planets: interaction of solar wind with planet environment
  - Exoplanets and their host stars
  - Stellar physics across the mass/age range
  - Supernovae: explosion mechanism, heavy element production
  - Stellar endpoints: dense matter
  - Interstellar dust and medium: composition
- Giant discovery space with ToO follow-up in the era of time domain astronomy

G. Branduardi-Raymont et al.



Jupiter X-IFU spectrum showing different line emission mechanisms

X-IFU key spectral requirements

- Spectral resolution: 2.5 eV up to 7 keV
  - Cluster physics (broadening down to 20 km/s) and missing baryons
- Energy band pass: 0.2 to 12 keV
  - Missing baryons
  - Black hole spins, winds and ultra-fast outflows
- Background requirement: $<5\ 10^{-3}$ counts/s/cm^2/keV (E> 2 keV)
  - Cluster physics and cluster chemical evolution

X-IFU key imaging requirements

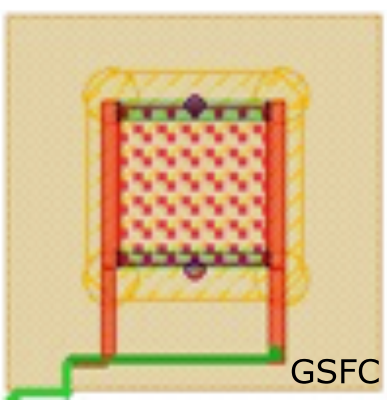
- Field of view: 5′ (equivalent diameter)
  - Cluster physics out to their outskirts
- Pixel size: <5 arcsec
  - Cluster feedback on relevant spatial scales and to minimize confusion
    - ➡ A new pixel size is being defined: 275 μm (4.7″) instead of 249 μm (4.3″) to reduce the overall number of pixels from 3840 to 3168

X-IFU key timing requirements

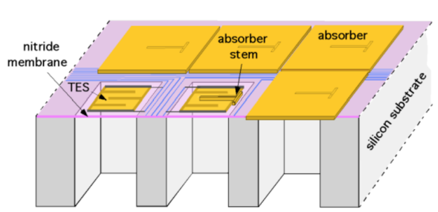
- 2.5 eV throughput for point sources: 80% at 1 mCrab and 80% at 10 mCrab (Goal)
  - X-raying missing baryons with bright line of sights GRB afterglows and bright quasars
- 10 eV throughput for bright point sources: 50% at 1 Crab between 5 and 8 keV
  - Probing stellar mass black hole and neutron star accretion disks & winds
- 2.5 eV throughput for extended sources: 80% at 2 10^{-11} ergs/s/cm^2/arcmin^2 (0.2-12 keV, brightest knots of Perseus)
  - Cluster physics and feedback

TES array and focal plane assembly

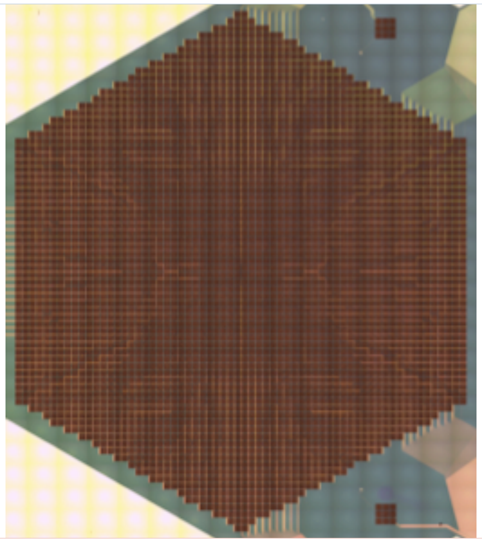
- 3168 Mo/Au Transition Edge Sensors of 275 μm pitch with absorbers of 1.7 μm of Au and 4.2 μm of Bi operated at ~100 mK, with an anti-coïncidence detector, all supported by a focal plane assembly



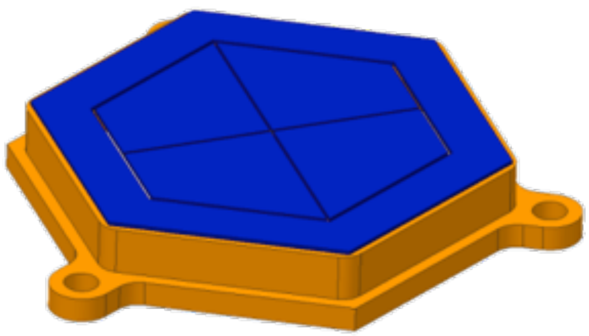
Stripe less 100-120 µm MoAu TES thermistor on SiN membrane (NASA)



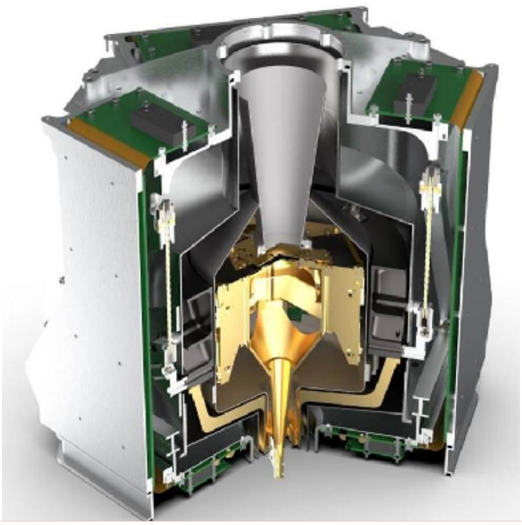
Filled-array of TES pixels with Au/Bi absorbers (NASA)



Large format array of TES (NASA)



TES cryogenic active anti-coincidence detector (<1 mm) (INAF)



Focal Plane Assembly Demonstration Model (SRON)

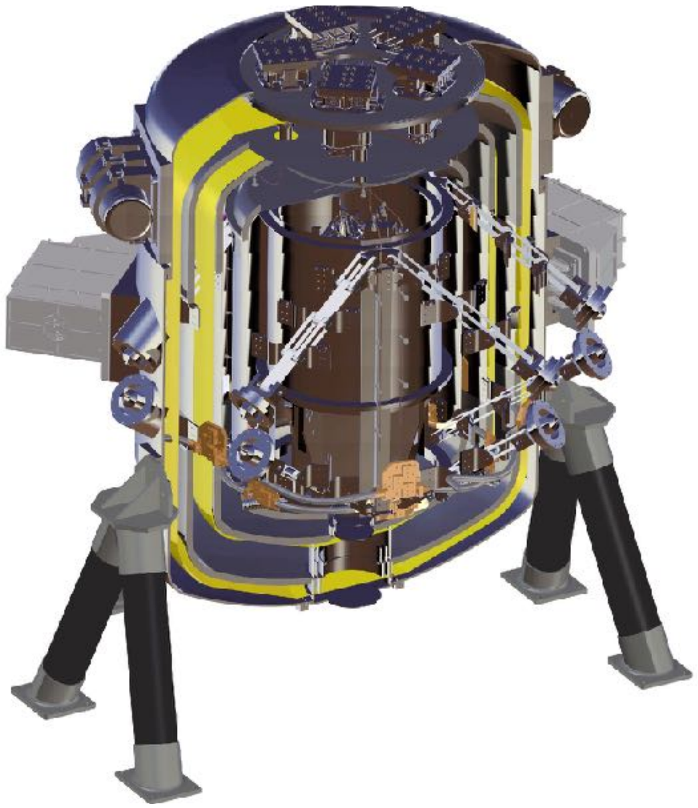
Barret+ and references therein

X-IFU cryogenic chain

- Multi-stage mechanical coolers:
  - Five 15K Pulse Tubes (ESA from ALAT)
  - Two 4K Joule-Thomson (JAXA)
  - Two 2K Joule-Thomson (JAXA)
  - One last stage 50 mK sorption-ADR (CEA-SBT)
- Thermal budgets within required margins with the outer vessel cooled at 200 K
  - Full redundancy at all stages but the last one
- Cool time of 32 hours and regeneration time of 8 hours
  - Regeneration cycle subject to optimization to maximize the X-IFU availability for 50 ks ToO observations

    ➡ 1 million counts for a GRB afterglow spectrum

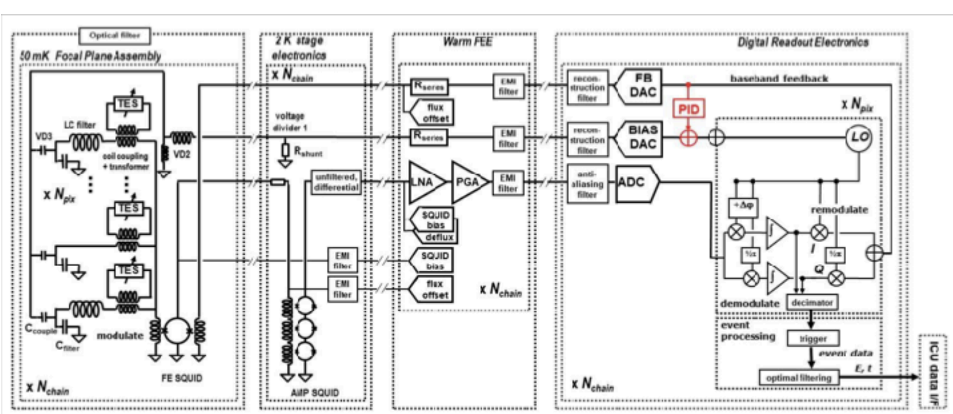
CNES project team



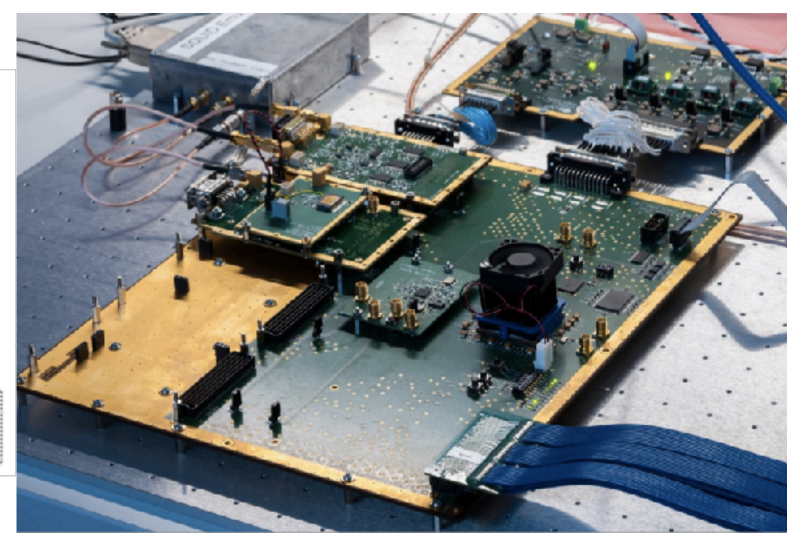
The X-IFU Dewar assembly — Final design optimization

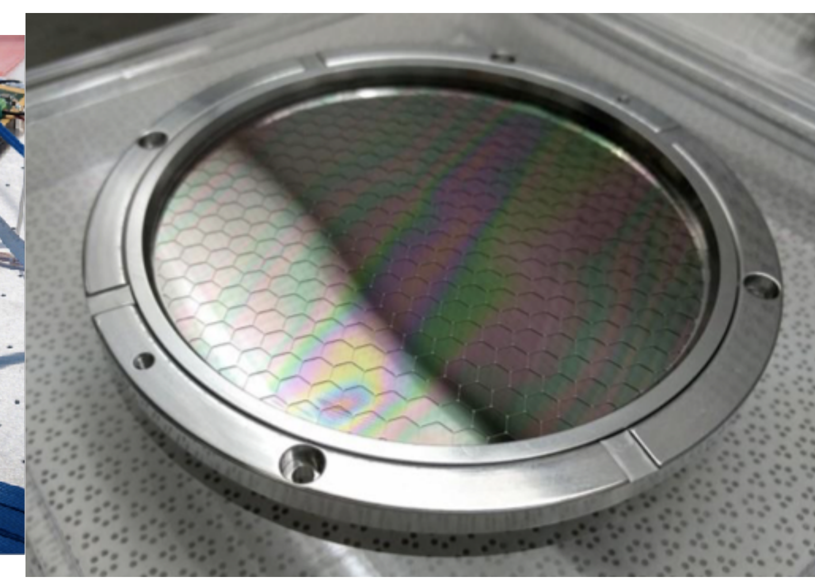
X-IFU key subsystems

- Frequency Domain Multiplexing (Time Domain Multiplexing as a backup)
- Optimized high transmission thermal and optical blocking filters
- Modulated X-ray sources for gain calibration
- Filter wheel for e.g holding optical and Be filters



The X-IFU readout chain (SRON)

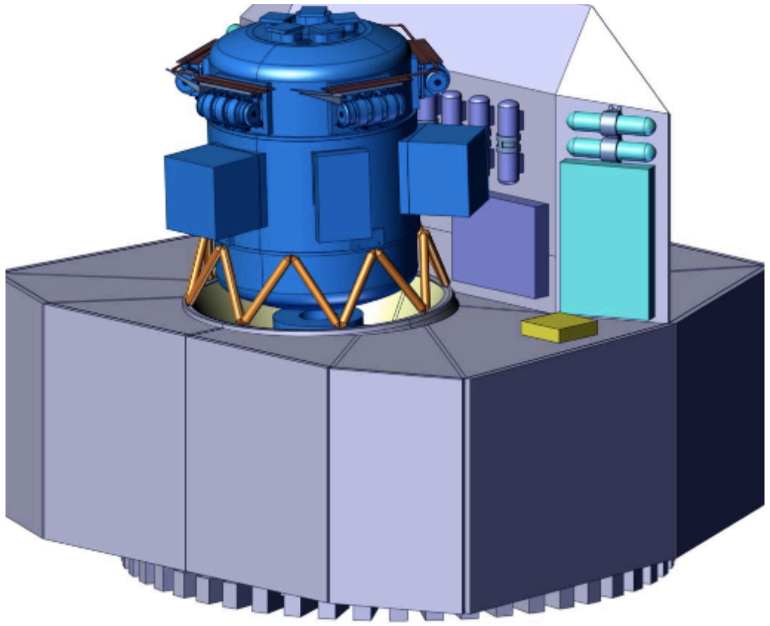

Digital Readout Electronics prototype (IRAP)


X-IFU filter sample (UniPa)

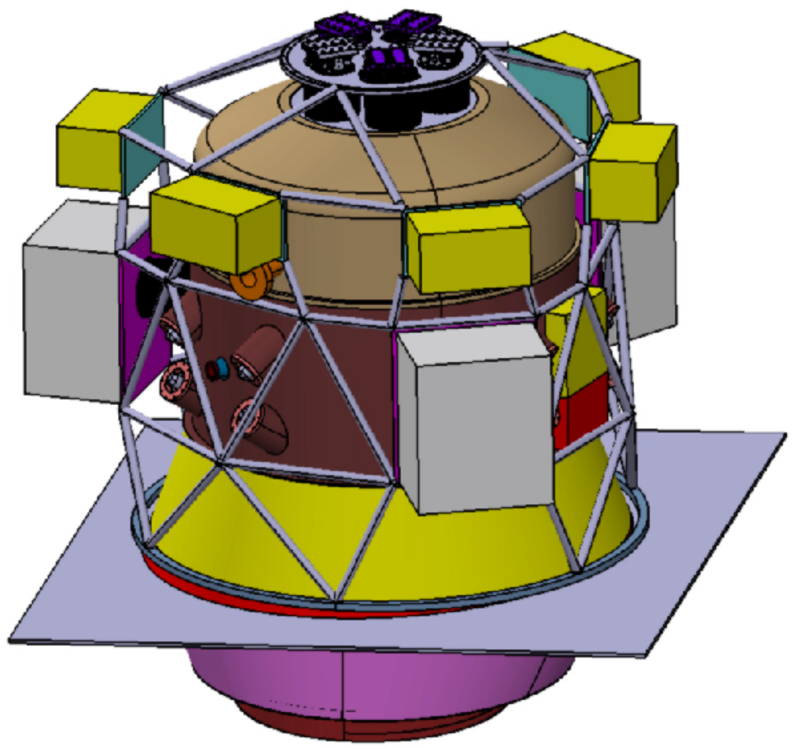
X-IFU instrument budgets

- Mass budget: ~770 kg (within allocation)
- Power budget: ~3.0 kW
- Last design iteration on the X-IFU accommodation on the Science Instrument Module
- Last design iteration of the Dewar
  - Separate the thermal and mechanical function of the cryostat and address e.g. micro-vibration issues
  - Addition of a separate supporting structure

M. Ayre (ESA study team)



X-IFU mounted on the Science Instrument Module

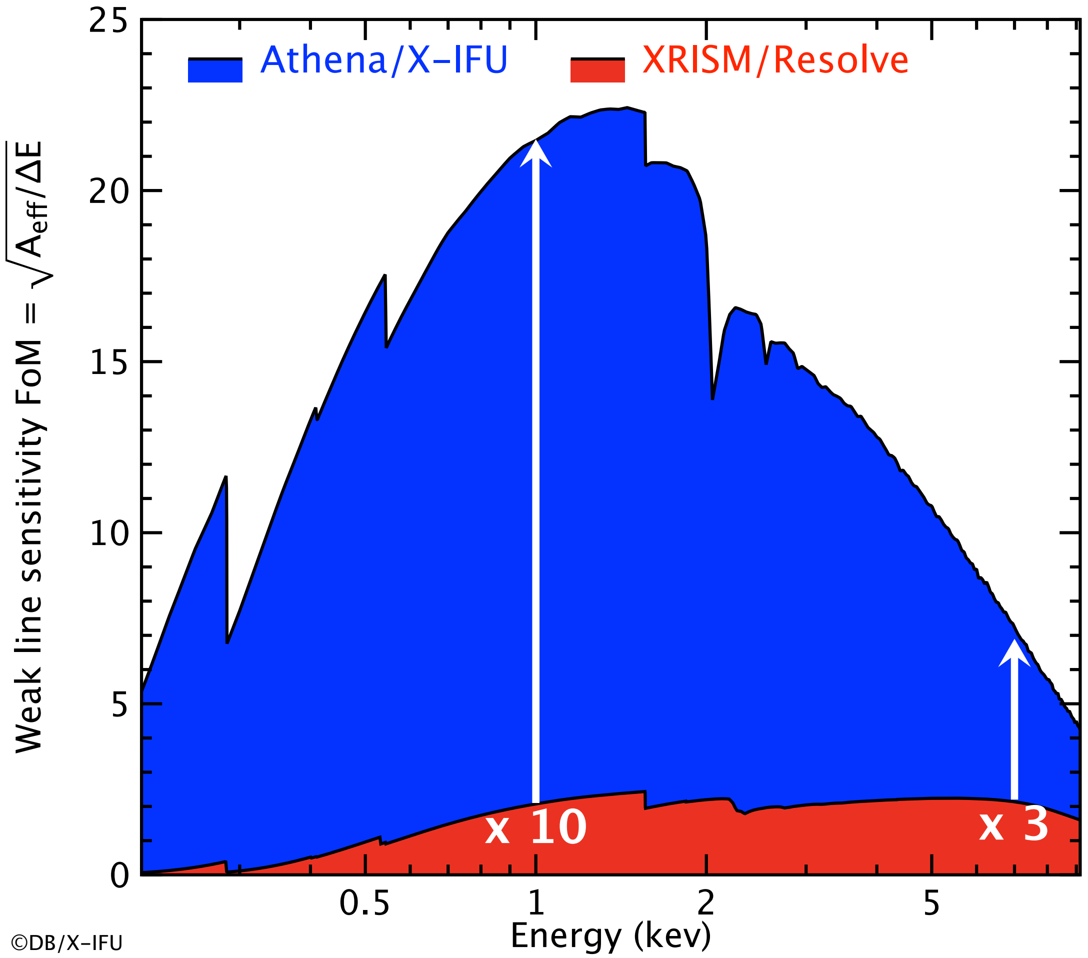


Latest X-IFU configuration

Weak line sensitivity

- Effective area is the product of the mirror effective area and the X-IFU filter attenuation and absorber stopping power
  - 45 times larger than XARM/Resolve @ 1 keV
- Weak line sensitivity scales like the square root of the effective area divided by the spectral resolution
  - Factor 10 better than XARM/Resolve due to better spectral resolution ~2.1 eV versus 5 eV and larger effective area

➡ Better imaging 1′ versus 5″ pixels

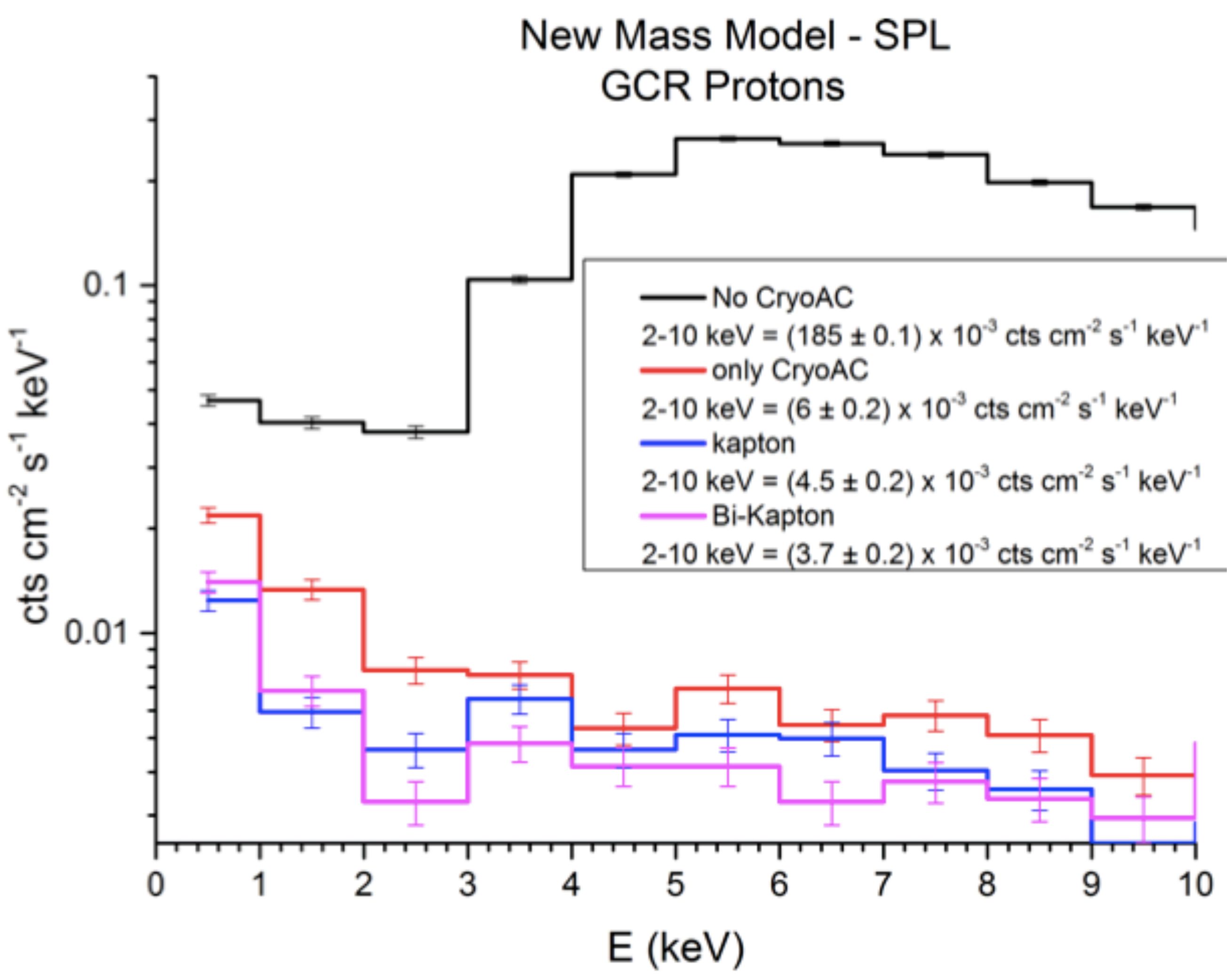


Weak line sensitivity comparison between X-IFU and Resolve

X-IFU background

- Latest GEANT-4 simulations indicate that the background requirement is met in worst case environmental conditions
  - Choice of materials surrounding the detector subject to further optimization to reduce yield of secondary electrons

Lotti et al.

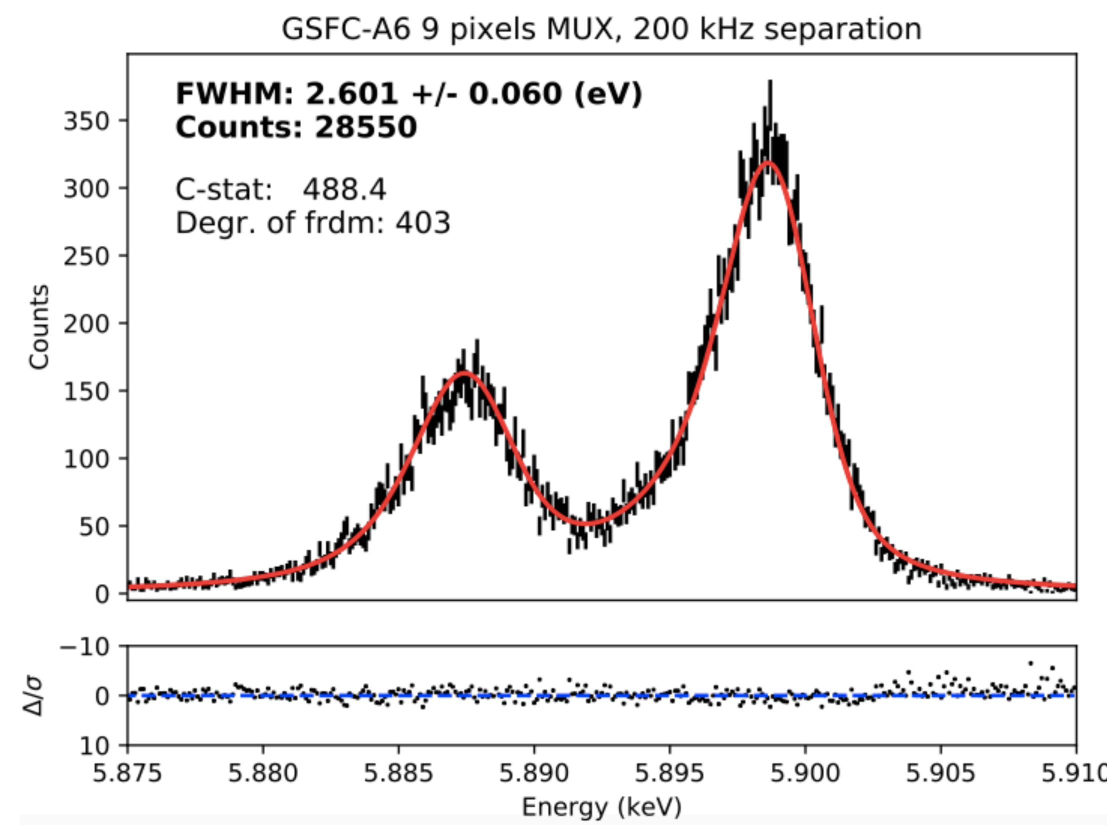


Background predictions under various assumptions

X-IFU spectral resolution

- Frequency Domain Multiplexing enables to read 40 pixels in one readout channel
- Achieving performance requires careful optimization of all the components of the chain from the TES, the cold front-end electronics, the warm electronics, the event processor
- Close to 2.5 eV routinely measured for multiplexed pixels
  - < 2 eV resolution measured on single pixel
  - Additional margins provided by the pixel optimization

Akamatsu et al.

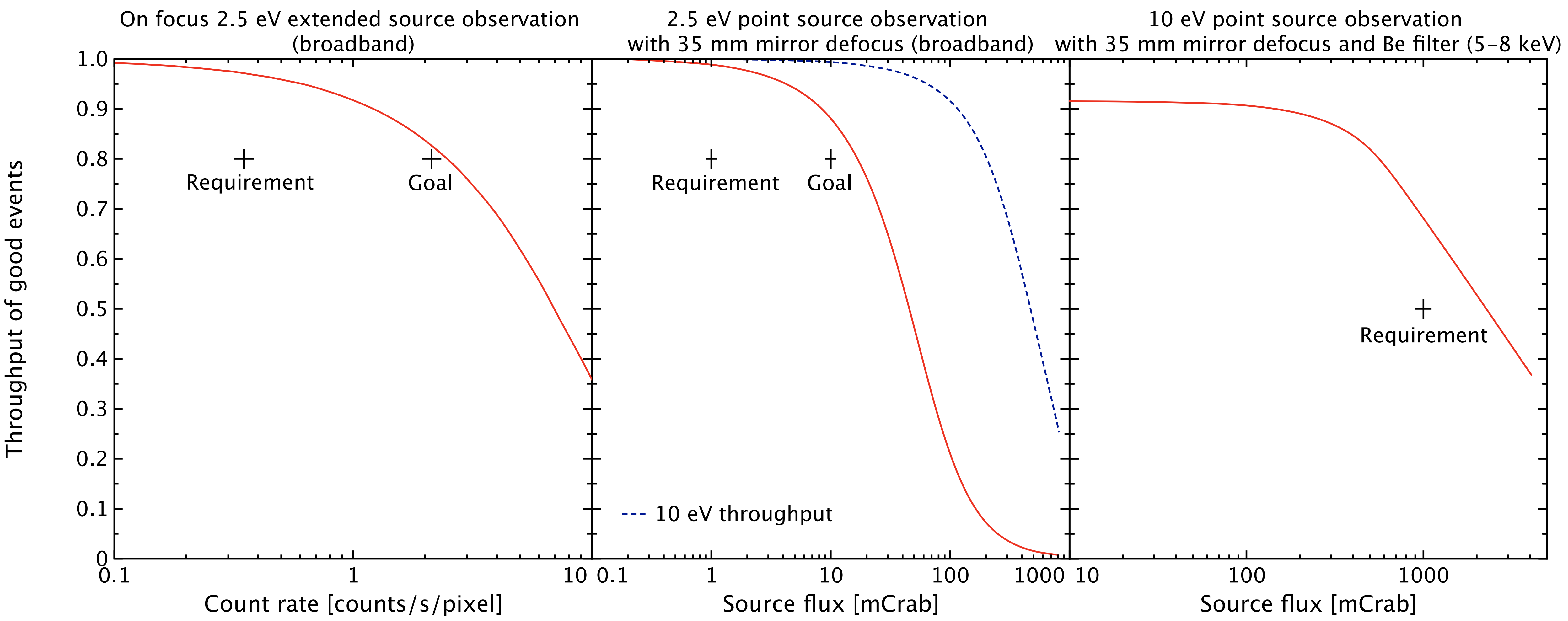


Spectral resolution achieved with FDM of 9 pixels

Barret+ 2018 and reference therein

Count rate performance

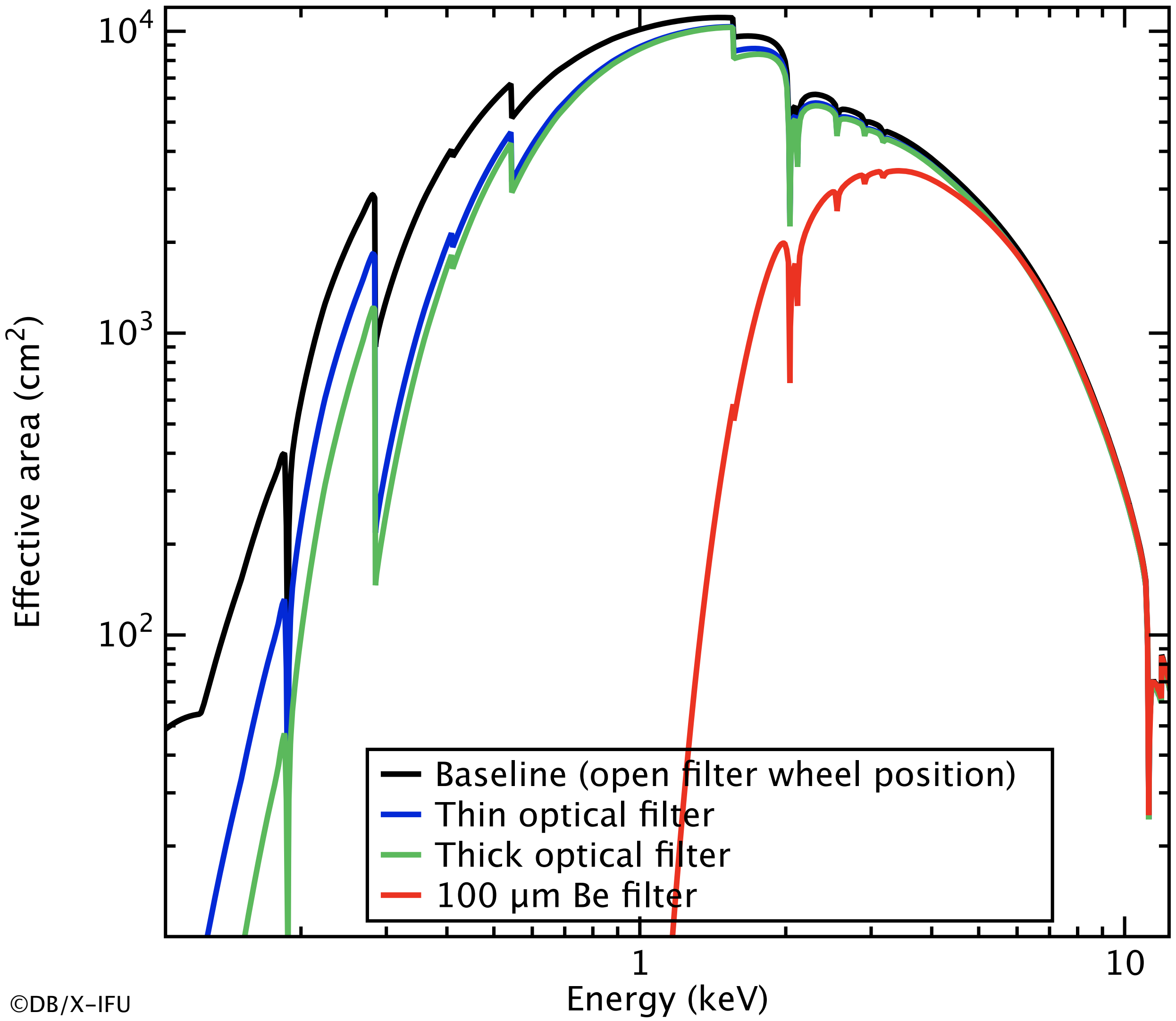
- Count rate performance is defined by the pixel speed, cross talk and record length required for achieving the spectral resolution
  - Defocussing of the optics enables to spread the PSF, hence very bright point sources can be observed



Count rate performance for faint extended sources, faint point sources and bright sources

Response matrices

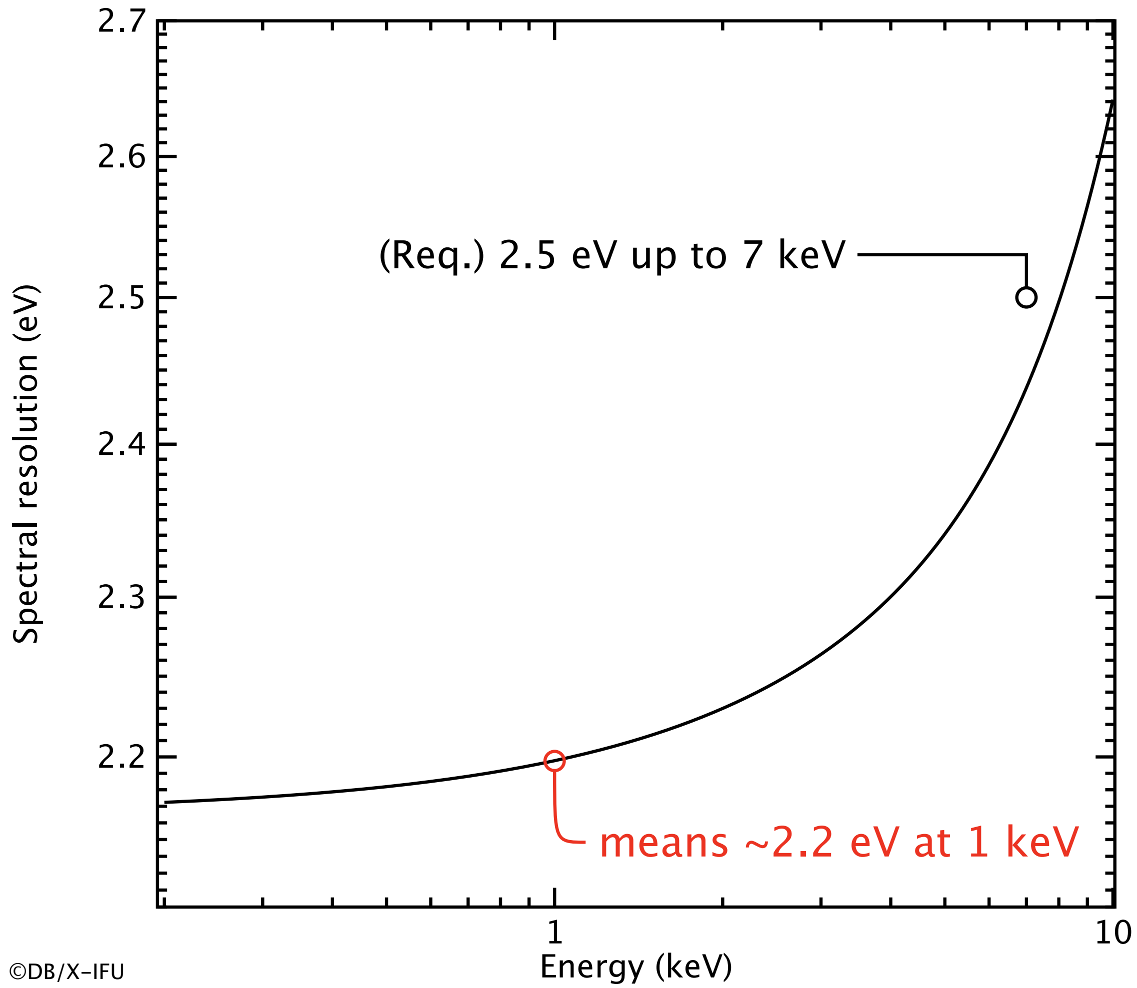
- Response matrices provided for:
  - No filter
  - Thin filter
  - Thick filter ($m_v < 7$)
  - 100 μm Be filter for bright X-ray sources



☞ http://x-ifu.irap.omp.eu

Spectral resolution

- Computed through detailed assessment of all components entering in the spectral resolution budget
- Requirement is 2.5 eV up to 7 keV
  - 0.5 eV margin in the budget
- Means ~2.2 eV at 1 keV
- New pixel functional parameters may further increase the margins (~0.7 eV rss) and improve the spectral resolution at 1 keV (~ 2.0 eV)
- Response matrix accounting for the spectral resolution variation available



☞ http://x-ifu.irap.omp.eu

Closing the phase A activities

- Consolidate the new mechanical design of Dewar assembly
  - New configuration is mass effective while addressing key issues, e.g. microvibrations
- Consolidate the new baseline for the functional parameters of the TES
  - May provide additional margins in the spectral resolution budget
  - Count rate capability margins enable to reduce their speeds so that they are easier to read by the electronics
  - Benefit of larger pixels may be used to reduce multiplying factor (hence provide additional performance margins) or reduce the number of readout channels (to save mass if need be)
- Consolidate critical technology & critical design demonstration activities
- Respond to the Instrument Consortia Consolidation call by October 1st, 2018
- Prepare the Instrument Preliminary Requirement Review (IPRR)

Conclusions

- X-IFU has revolutionary capabilities by combining high spectral resolution, fine imaging and high throughput up to the brightest X-ray sources
  - We have to anticipate that after XARM, X-ray astronomy will be a completely new field
- X-IFU has reached a stable and robust baseline configuration meeting its top-level performance requirements
  - All the components entering into the performance budgets are understood, closing now the last round of optimization
- Technology demonstration on key instrument components has made significant progresses : cooling chain demonstrator, TES and readout electronics, filters…
  - Technology plan in place to bring those key elements to TRL5 at mission adoption
- Next milestone: Instrument preliminary requirement review in Q1/19

Thanks to you and to all of them

IFU
ATHENA X-ray Integral Field Unit

irap
astrophysique & planétologie

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

SRON
Netherlands Institute for Space Research

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI DI ROMA

cnrs INSU
Observer & comprendre

UNIVERSITÉ TOULOUSE III PAUL SABATIER

Observatoire Midi-Pyrénées OMP

NWO

asi agenzia spaziale italiana

Consiglio Nazionale delle Ricerche

cea

INAC INSTITUT NANOSCIENCES ET CRYOGÉNIE

sbt

INTA

CSL CENTRE SPATIAL DE LIÈGE

Université de Liège ULg

NÉEL institut

VTT

UNIVERSITY OF HELSINKI

INAF ISTITUTO NAZIONALE DI ASTROFISICA — ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

INAF ISTITUTO NAZIONALE DI ASTROFISICA — ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI MILANO

INAF ISTITUTO NAZIONALE DI ASTROFISICA — OSSERVATORIO ASTRONOMICO DI PALERMO

INAF ISTITUTO NAZIONALE DI ASTROFISICA — ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI PALERMO

Università degli Studi di Palermo

Università degli Studi di Genova

INFN

IFN Institute for Photonics and Nanotechnologies

APC

UNIVERSITÉ DE GENÈVE

CBK PAN

IFCA Instituto de Física de Cantabria

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

UC UNIVERSIDAD DE CANTABRIA

ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

INAF ISTITUTO NAZIONALE DI ASTROFISICA — OSSERVATORIO ASTRONOMICO DI ROMA

UCL MSSL

UNIVERSITEIT VAN AMSTERDAM

Universiteit Leiden

Universitat d'Alacant
Universidad de Alicante

HIROSHIMA UNIVERSITY

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

IAS Orsay

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

esa

NASA

NIST

STANFORD UNIVERSITY

JAXA

ISAS